GRAIN SURFACE FEATURES AND CLAY MINERALOGY OF THE QUATERNARY SEDIMENTS FROM WESTERN DECCAN TRAP REGION, INDIA, AND THEIR PALAEOCLIMATIC SIGNIFICANCE

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Abstract
Quartz sand grains obtained from a deeply gullied topography along the banks of two tributaries of River Pravara in Maharashtra (India) have been examined with a scanning electron microscope (SEM). Quartz grains have been selected after a heavy mineral separation and micro-photographs of each grain were taken at various angles and magnifications. The sediments reveal features resulting from mechanical grinding as well as from chemical alteration. Conchoidal fractures, cleavage planes, grooves, v-shaped indentations etc. are the mechanical features documented on the grains whereas solution pits of varying sizes and intensity, precipitation surfaces, oriented v-pits, solution crevasses and etching are the features of chemical origin. Several evidences indicate that the samples have undergone digenetic changes. Few grains show the features of intense chemical breakdown. The overall assemblages of the grain surface features suggest that the samples have been subjected to subaqueous transport for a considerable period of time. The minor chemical features such as solution pits or semi circular arcuate steps found in abundance on these grains are due to the dissolution of the sediments in a low energy fluviatile environment. For clay mineralogy, fractions between <2 and <0.2 mm were separated out from the sediments. The clay fractions were then subjected to examination by X-ray diffraction (XRD) of oriented K/Ca saturated samples using a Philips Diffractometer and Ni-filtered Cu Ka radiation with the scanning speed of $1^0\ 2\Theta\ \min^{-1}$. The main clay minerals for all the samples are identical and show the presence of hydroxy-interlayered smectites with minor quantities of mica, kaolinite, smectites, quartz and feldspar. The first weathering product of the Deccan Basalt (DB) is the dioctahedral smectite. Since the present semi aridic climatic condition of the study area can not transform a smectite to HIS and either smectite to kaolin, it is quite likely that both the HIS and Sm/K are generated in the tropical humid climate of the Western Ghats and then carried through the exiting river system like Godavari, Adula and Mahalungi. Therefore it is evident that the clay minerals present in these sediments represent another climatic history more humid than the one prevailing at present.

Keywords: X-ray diffraction, hydroxyl-interlayered smectites, SEM, subaqueous, conchoidal fractures, cleavage planes, grooves.

1. Introduction

Ocean floor records based on the oxygen isotope studies and geochemical records, together with the palaeontological evidences and radio carbon dating of the sediment facies revealed that Quaternary Period is characterized by climatic fluctuations (Bowen, 1978). Terrestrial Quaternary records represent a unique environment and the palaeoenvironmental, palaeoecological and palaeoclimatic information derived from them forms an integral part of global understanding of climatic change (Kale, 1996). The understanding of sedimentary facies of terrestrial sequence is of vital importance as it is embedded with stratigraphically representative records (Schluchter, 1992). Quaternary sediments cover an area of 6,00,00 km^2 of the Indian subcontinent and are found in several places including Karewas of Kashmir, Siwaliks of northwestern India, Central Narmada and Upper Godavari Basin, Kurnool caves of South India and eastern and western coast of India (Badam, 1979). The present study is an attempt to understand the palaeoclimatic history of a region through the study of sedimentary records documented in the area.

The area under review falls in a semi-arid tract of the Western Upland Maharashtra which is a part of the Deccan Trap Region, in India. The location of the study area is shown in Fig. 1.

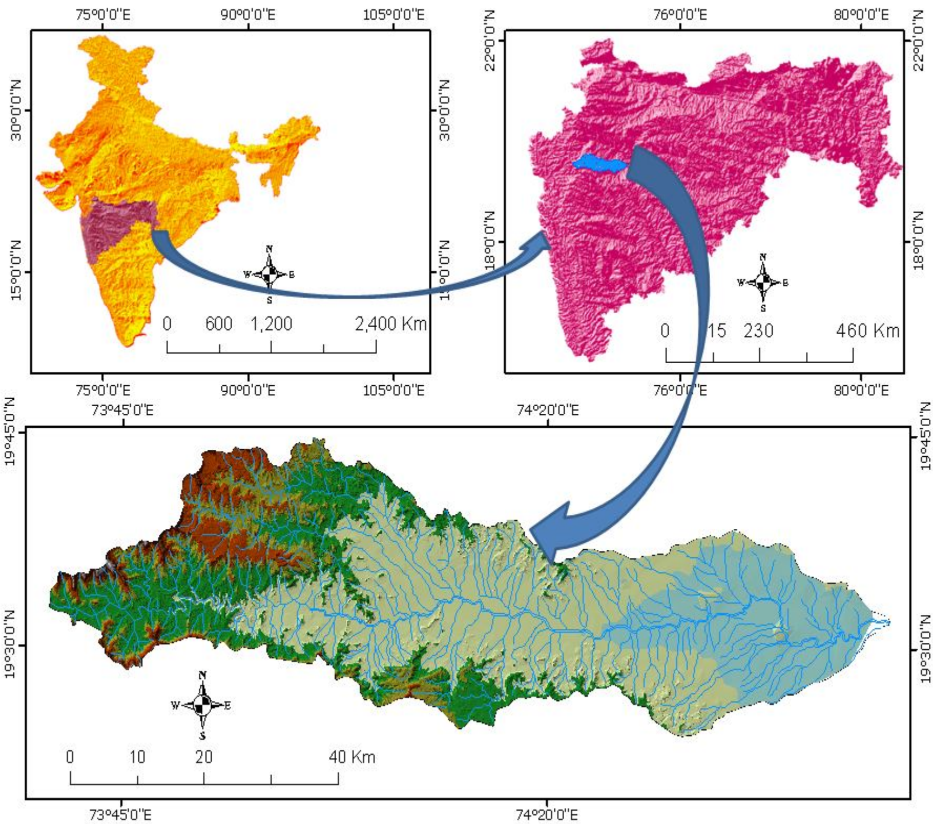


Fig 1. Map of the study area.

The Trap Region is essentially characterized by dearth of sediment since the region exhibits an erosional topography. Thick and expansive sedimentary reservoirs are distinctly few and cover only a few restricted locations, such as narrow banks of rivers and along a few foothill pediment zones. The alluvial deposits of the Godavari Basin have been investigated to reconstruct the denudation chronology by Kale and Rajaguru (1987) and Joshi and Kale (1997) emphasized the role of colluvial deposits along the foothill zones of Western Maharashtra to understand the Quaternary climatic changes. The study area is one of the few sites where sediments of nearly 10 m thickness cover the channel banks. Currently these sediments are undergoing rapid erosion; it is obvious since gully erosion produced a hummocky appearance. River Pravara is a major tributary of Godavari River in Maharashtra. Along the banks of Pravara and two of its tributaries, the alluvial banks have been deeply dissected to form badlands. Both tributaries are very close to the source region of the river. The tributaries are flowing from west to east and are flanked by hill ranges in the north and south, running parallel to the streams. The thickness of these alluvium ranges from a few meters to about ten meters, which gradually merges to the pediments of these hill ranges. These Quaternary sediments rest over basaltic rocks of Cretaceous-Eocene origin. Two properties of these alluvial sediments that have the palaeoclimatic significance have been analyzed to infer the past history and also to understand the source region of these sediments.

In this study, clay mineralogy and the grain surface features photographed under scanning electron microscope have been used to understand the palaeoclimatic conditions as well as the source areas of these sediments. These two sediment properties have been emphasized here because the interpretative values of both parameters are very significant to understand the past environmental conditions that affected the sediment deposition.

The significance of clay minerals is in their interpretative value in terms of the source material as well as the physical properties that they influence. Several soil scientists have studied different aspects of clay minerals (Pal et al. 1989, 2001; Pal and Deshpande, 1989; Balpande et al. 1996; Chandran et al. 2005; Battacharyya et al. 1993, 1999 and Srivastava et al. 2002) and associated soil properties (Murthy et al. 1982; Blokhuis et al. 1990; Delvaux et al. 1990a and 1990b; Nimkar et al. 1992; Paranjape et al. 1997; Vaidya and Pal, 2002 and Pal et al. 2006). According to Pal (2003), the hurdles, that often mislead us regarding the proper identification of clay minerals in a soil profile, let only use it to interpret their significance in soil genesis and properties. Thus, it is important to identify soil clay mineralogy in order to understand their environmental significance.

The grain surface features also have the diagnostic properties of the sedimentary environment of the deposits from which they have come. Such diagnostic surface features are viewed and photographed by a scanning electron microscope (SEM) on the quartz grains on sediment samples collected from different similar environments. The shapes of clastic particles and microscopic textural patterns on their surfaces are repositories of information about the physical and chemical processes which the particles have been subjected to. The interpretative value of these features to discriminate geological and geomorphological processes has been made popular by the works of Krinsley and his several co-authors during the 60s and 70s including Krinsley and Funnel (1965), Krinsley and Donahue (1968), Doorncamp and Krinsley (1971) and Krinsley and Doorncamp (1973). Following these, several other investigations have been published in various international journals that focus on similar issues. The number of studies, that use SEM techniques to evaluate geological and geomorphological processes, is also significant. There are some examples: Singh (1975), Manickam and Barbaroux (1987), Tiwari et al. (2001) and Tiwari et al. (2004).

2. Material and Methods

2.1 Sediment profile site and characteristics

Along the Mahalungi River which is a tributary of the River Pravara in Godavari Basin, two lithosections have been examined: one in the source area and the second one is situated about 18 km downstream from the previous site where the stream meets another tributary named Adula.

- First Site: The thickness of this exposure is 28 m. The sediment section demonstrates a typical fluvial sequence including several alternating layers of perfectly horizontal sandy facies with coarser pebbly facies as well as finer silty-clayey facies. Cut and fill structures and sandy troughs are common. Subsidiary and large sediment composition is dominated by silty and fine sand material. Five samples have been collected from different lithofacies from this section.
- Second Site: The thickness of this section is 5 m. Gravelly pebbly and sandy facies with horizontal bedding are predominant in this profile. The top upper part and the lowermost parts of the exposure show finer silty facies with massive structure. From this section five samples have also been collected depth wise from the surface.

2.2 Laboratory analysis

In order to study the general textural characteristics of the sediments, the samples were subjected to granulometric analysis using an X-ray based sedigraph machine. Additional two samples collected from the bed of the gullies have also been incorporated in the analysis. Grain size distribution of the sediment is a function of the size range of available material, its accessibility for weathering, erosion and transportation, and the input of energy into the sediments. The particle size statistics of these samples were calculated using Folk and Ward (1957) method.

For SEM analysis heavy and light minerals were separated after treatment, and the quartz grains have been selected for the analysis. The selection of quartz grains was difficult due to the paucity of these grains in the sample. Ten samples were selected and a hundred grains were finally used from these samples for the analysis. The selected grains were coated with platinum, put on double sticker carbon conducting tape and mounted on a stub, which are arranged in two rows and put into JEOL-JSM-6360A Analytical Scanning Electron Microscope, then micro-photographs were taken at various angles and magnifications.

For the identification of clay minerals, the international pipette method (Jackson, 1979) was applied for the separation of clay fractions (<2 and <0.2 mm) from the sediments after the removal of organic matter, calcium carbonate and free iron oxides. The clay fractions were examined with X-ray diffraction (XRD) of oriented K/Ca saturated samples using a Philips Diffractometer and Ni-filtered Cu α radiation. The scanning speed was $2^0 2\Theta$ min^{-1}. The minerals were identified using the method described by Jackson (1979).

3. Results

3.1 Granulometric analysis

Grain size analysis is an integral part of the sedimentological studies. The size of sand grain particle cannot be uniquely defined though the term ‘size’ commonly used in sedimentology. According to Pettijohn (1984), the main aim of grain size analysis is to provide a data that can accurately describe sediments. The main aim of the granulometric analysis in the present work is to understand the type of sediment population that characterizes these deposits, and it will not be explored further to interpret the details of the depositional environment for which the techniques are usually applied. The result of the analysis is presented in Fig. 2.

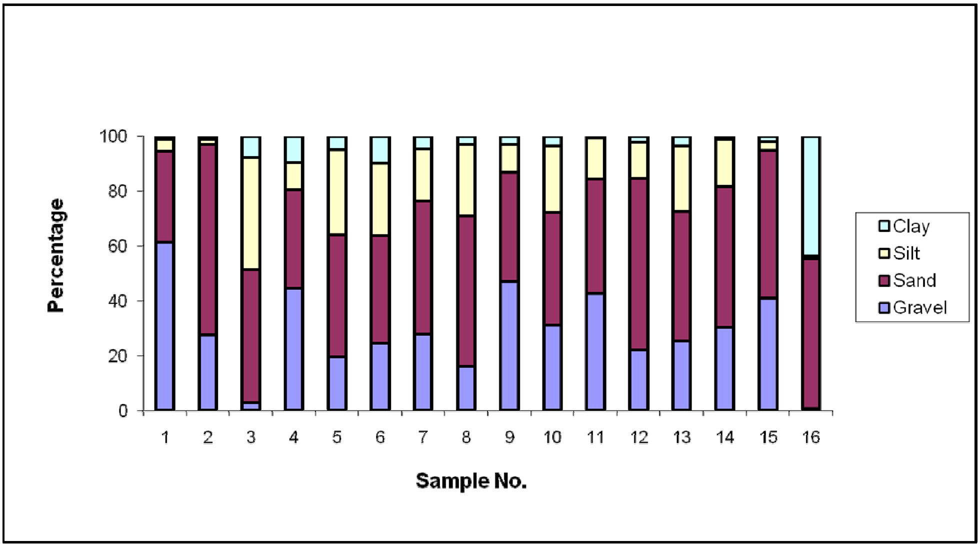


Fig. 2. The general textural characteristics of the sediments.

It can be seen that the particle size ranged between clay and gravel and is dominated by sand and silt fraction in size population. Sand-silt percent constitute for more than 70% in almost all the samples analyzed. The particle size statistics of these samples were calculated using the Folk and Ward (1957) method, and it demonstrates that all the samples are very poorly sorted indicating variability in energy level of the depositing medium (Table 1).

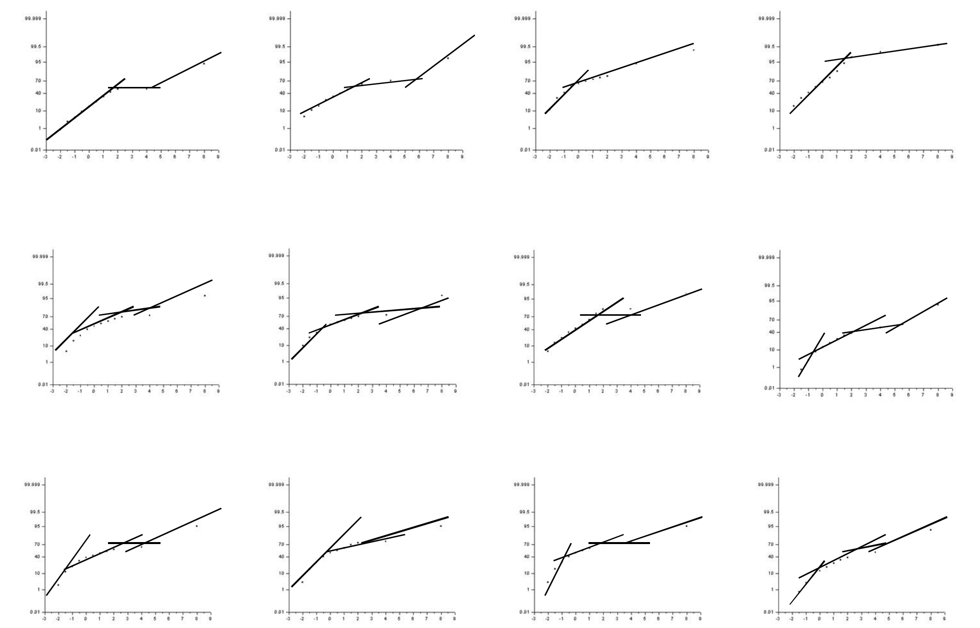
Mean phi size range in a wide spectrum such as from -0.96 to 6.73. Skewness is positive for almost all the samples except two, suggesting predominance of finer fractions in the entire sediment population. Kurtosis varies between 0.6 and 2.5 that implies that the sediments are between the low peaked platykurtic and the strongly peaked leptokurtic in the category indicating again the variation in the energy level of the depositing medium.

Three straight line segments can be identified in the figures, which represent three sediment populations such as surface creep (lowest segment), saltation (middle segment) and suspension population (uppermost segment). Additional truncation points within the saltation population can also be observed within the population in few samples.

Table 1. Grain Size Statistics of the Sediments.

Sr. No.	*Mean size in ϕ*	*Sorting in ϕ*	*Skewness in ϕ*	*Kurtosis in ϕ*	*Sorting Category*
1	3.08	3.23	0.32	0.64	Very poorly sorted
2	2.33	2.69	-0.38	0.77	Very poorly sorted
3	3.96	4.12	0.68	0.54	Extremely poorly sorted
4	0.38	2.68	0.64	1.19	Very poorly sorted
5	1.08	2.75	0.44	0.80	Very poorly sorted
6	1.13	3.01	0.51	0.65	Very poorly sorted
7	0.54	2.26	0.22	1.47	Very poorly sorted
8	-0.96	1.42	0.56	1.93	Poorly sorted
9	1.75	3.03	0.29	0.72	Very poorly sorted
10	1.25	3.03	0.57	0.88	Very poorly sorted
11	-0.17	2.09	0.46	1.31	Very poorly sorted
12	-0.63	1.29	0.20	0.72	Poorly sorted

The grain size log probability plots (Visher, 1969) of the studied samples are demonstrated in Fig. 3. The use of log probability plots to study grain size is more expressive than using other curves such as the log of the grain size with the frequency percent or cumulative frequency percent, since it normally shows two or three straight line segments, and the tails of the simple ‘S’ shaped cumulative frequency curve appear as straight line (Visher, 1969). Thus, samples and measurements can be easily compared. According to Krumbein and Aberdeen (Cf- Visher, 1969), all clastic sediments are the mixtures of three or less log-normally distributed populations. In this analysis, the plots revealed the presence of three well-developed populations in most of the samples namely surface creep, saltation and suspension. The interpretation of this distribution is that it represents three separate log-normal populations. Each population is truncated and joined to the next population in order to form a single distribution. This means that grain size distribution do not follow a simple log-normal law, but consists of several log-normal populations, every one with different mean and standard deviations. Some samples indicate the presence of just two populations such as saltation and suspension population. Few samples show additional breaks in saltation population (T3). The determined percentages of these populations and their truncation points are given in Table 2.



Cumulative frequency percent (Y) against phi size of the sediments (X)

Fig. 3. Log probability plots of sediment samples

The occurrence of truncation points between saltation and rolling population shows a great variability of the phi value, ranging between -1.2 phi and 1.7 phi. The same observation is taken regarding the next break between saltation and suspension population. Subsidiary and large sorting is poor for all the samples in all the three populations, but creep population shows better sorting than both the suspension and the saltation population with a slope up to 50^0 for creep carpet, 4^0 and 40^0 for saltation and suspension respectively. Sorting is a very important index in the grain size studies because it is the measure of the population mixing that reflects the flow regime prevailed during the sediment transport. Hence poor sorting of the samples here as well as variable locations of the truncation points between the populations suggest thorough the sediment mixing as a result of varying flow regimes during their deposition. A few samples show only the two populations of saltation and suspension. The shapes of these log probability plots with better sorted surface creep population and better sorted saltation compared to poorly sorted suspension population, where there are two segments,, are similar to the plots of fluvial sediments given by Visher (1969). Therefore it suggests that these sediments were deposited under the variable flow conditions of a fluviatile environment.

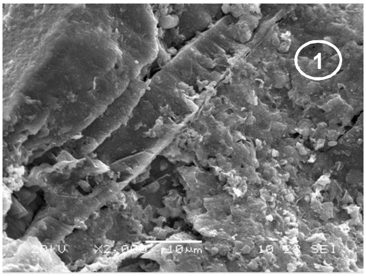
Table 2. Determined percentages of the sediment populations and their truncation points

	Surface Creep %	Saltation %	Suspension %	T1 Truncation point 1	T2 Truncation point 2	T3 Truncation point 3
1	55	10	33	1.7	4.5	-
2	60	10	27	1.6	5.8	-
3	65	30	-	-0.2	-	-
4	96	4	-	1.6	-	-
5	50	30	18	0	1.7	4.8
6	55	25	19	-0.2	2.1	5.5
7	80	10	9	1.7	4.1	-
8	10	40	46	-0.7	2.2	5.5
9	30	30	37	-0.9	2.3	4.2
10	65	10	23	0.5	4	-
11	30	45	22	-1.2	2.3	4.9
12	7	50	40	-1	2.7	4.7
Average	50.25	24.5	24.45	-	-	-

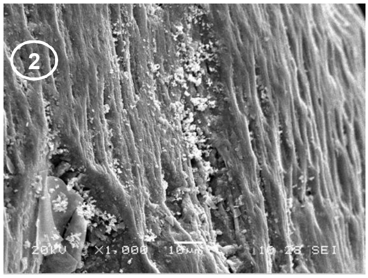
3.2 SEM Results

Under SEM examination the basic shapes of the grains are angular to sub-round in nature. It is noteworthy to mention that the grains show equal percentage of mechanical as well as chemically formed features. There are features due to the mechanical breakage such as conchoidal breakage pattern, fractured blocks, upturned plates, arc shaped semi parallel steps, flat cleavage plates and mechanical v-pits. Most of the grains show medium to high energy chemical alterations, such as deep etching, solution pits, razor sharp hacksaw terminations and oriented v-forms. In some photographs there are silica precipitation and adhering particles as well. All the 100 grains were examined but some grains were photographed many times from various angles and magnifications, hence these grains ultimately provided several microphotographs.

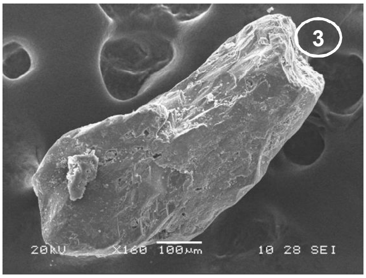
SEM at 2000 X. SEI shows mechanical fracture and adhering particles on the grain surface



SEM at 1000 X. Grain surface depicts conchoidal breakage and the adhering particles



SEM at 160 X. An elongated grain with v – shaped indentations.



SEM at 3,500 X. Grain surface shows cleavage planes, with precipitation In the lower part

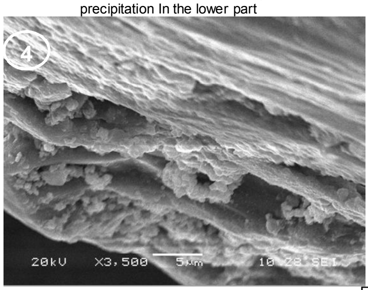
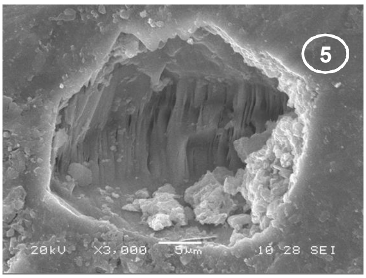
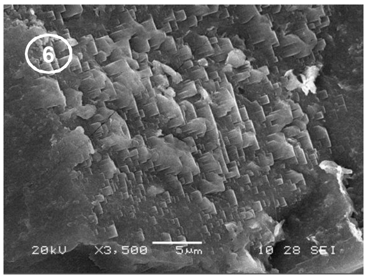


Fig 4a

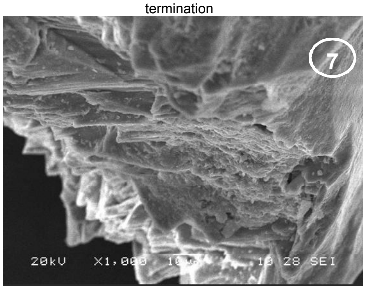
SEM at 3000 X. Grain shows solution pit with deep etching



SEM at 3,500 X. Grain surface depicts preferential solution along cleavages



SEM at 700 X. Grain shows razor sharp hacksaw termination



SEM at 1,600 X. Grain surface shows grooves.

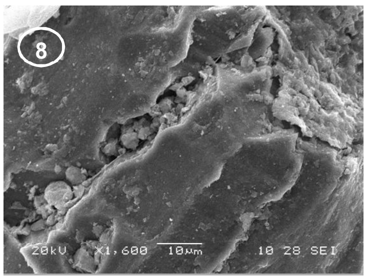
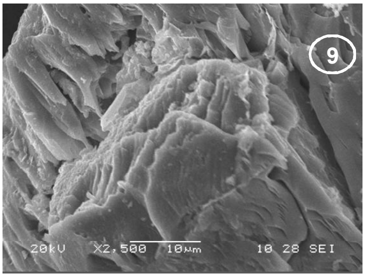
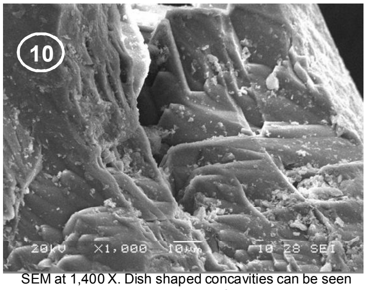


Fig 4b

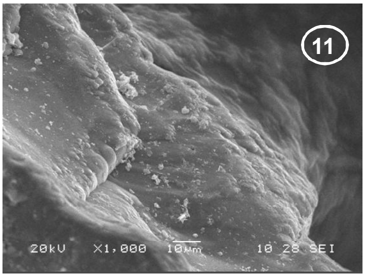
SEM at 2,500 X. Grain surface demonstrates solution crevasses



SEM at 1000 X. Grain shows chemically formed v – etch pattern.



SEM at 1000 X. Globular protuberances



SEM at 1,400 X. Dish shaped concavities can be seen on the grain surface

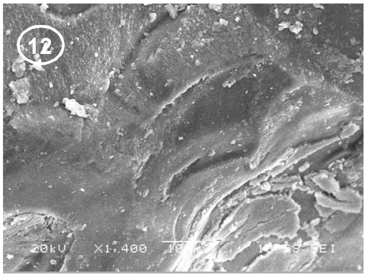


Fig 4c

Fig. 4a. Grain surface features of few grains magnified at different magnitudes and photographed under an electron microscope. All the photographs show features of mechanical origin, such as 1) mechanical fracture 2) conchoidal fracture 3) mechanical v-pits and 4) cleavage planes. Adhering particles and precipitations are also documented in these grains.

Fig. 4b. Features derived from subaqueous environment and intense chemical etching are demonstrated in these images. Photo 5 shows a solution pit which is the proof that the feature was formed under low energy fluviatile environment. The rest of the photographs (3 pcs.) shows the marks of intense chemical weathering on grains.

Fig. 4c. Solution crevasses, chemical v-indentations, globular protuberance and disc shaped concavities are the features found on these grains. The chemical origin of them is proven. The v-patterns in photo no. 10 demonstrate preferred orientations of the solution crevasses because they are guided by the fractures on the grain.

From them, distinctly different features were selected and reproduced in Fig. 4a, 4b and 4c, and the frequency of the features documented on the grains are presented in Fig. 5.

Fig. 4a groups four SEM microphotographs of mechanical origin. Parallel conchoidal fractures are clearly visible in the photograph 1, with the adhering particles. The photo 2 reveals conchoidal breakages, and mechanical v-pits are documented in the 3rd photograph. The last photo shows silica precipitation within the oriented cleavage planes. Fig. 4b depicts photographs of digenetic origin, such as solution crevasses, etching, hacksaw terminations and grooves. The features that are the results of intense chemical alterations such as v within v that are chemically induced or globular protuberance is shown in Fig. 4c.

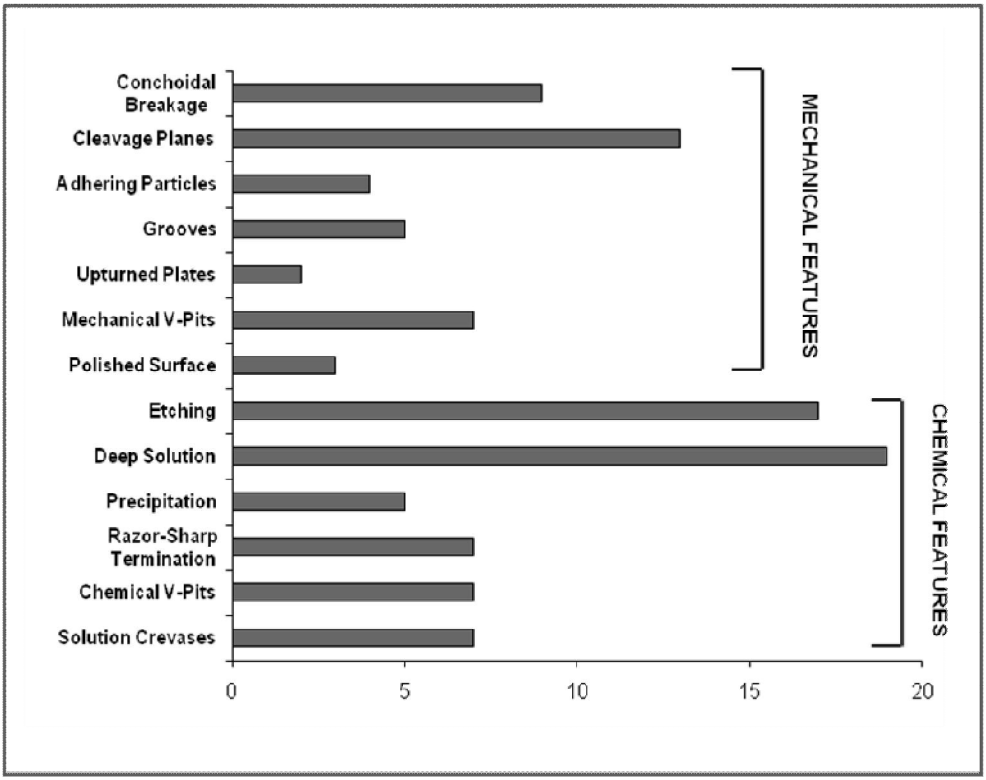
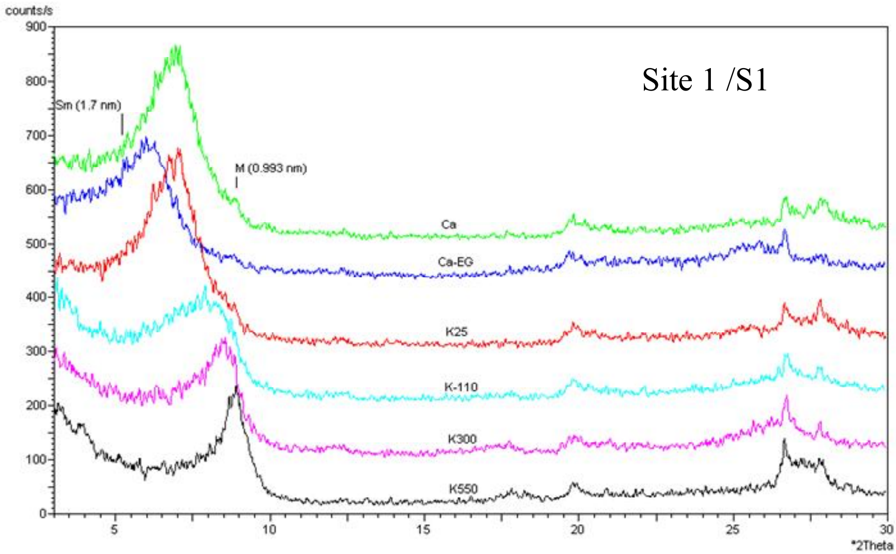


Fig. 5. The frequency of surface features documented on the grains, from SEM photographs.

3.3 X-Ray Diffraction Pattern

X-ray diffraction methods generally consider the distinction among different clays based on the expansion or contraction of the interlayer space – the region between adjacent 2:1 or 1:1 layers – in the presence of different cations and solvents (Brown and Brindley, 1980). It allows not only to identify specific clay minerals from complex mixtures but can also provide semiquantitative estimates of their abundance (Brown and Brindley, 1980). XRD of 10 samples, 5 from two lithosections have been conducted and the graphs are shown in Fig. 6a to 6c (first section) and Fig. 6d to 6f (second section).


counts/s
Site 1 /S1
Sm (1.7 nm)
M (0.993 nm)
Ca
Ca-EG
K25
K-110
K300
K550
°2Theta

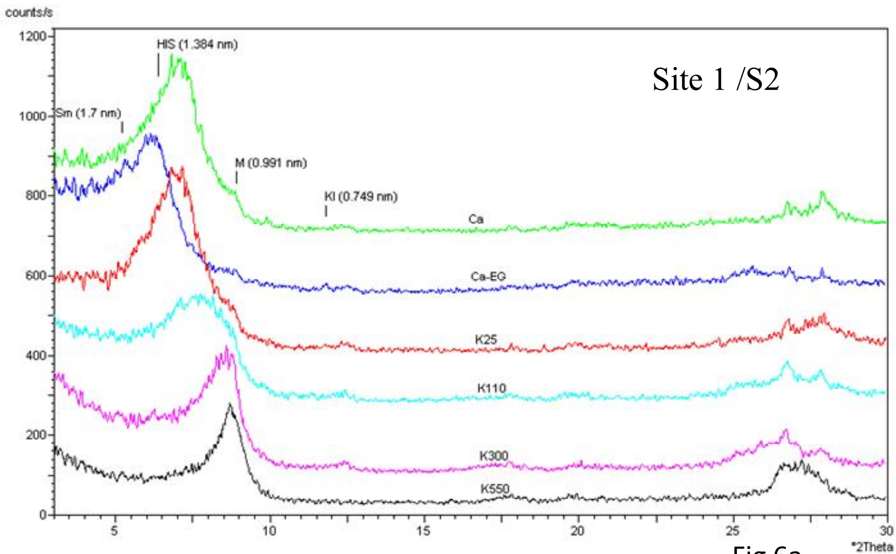

counts/s
HIS (1.384 nm)
Site 1 /S2
Sm (1.7 nm)
M (0.991 nm)
Kl (0.749 nm)
Ca
Ca-EG
K25
K110
K300
K550
°2Theta

Fig 6a

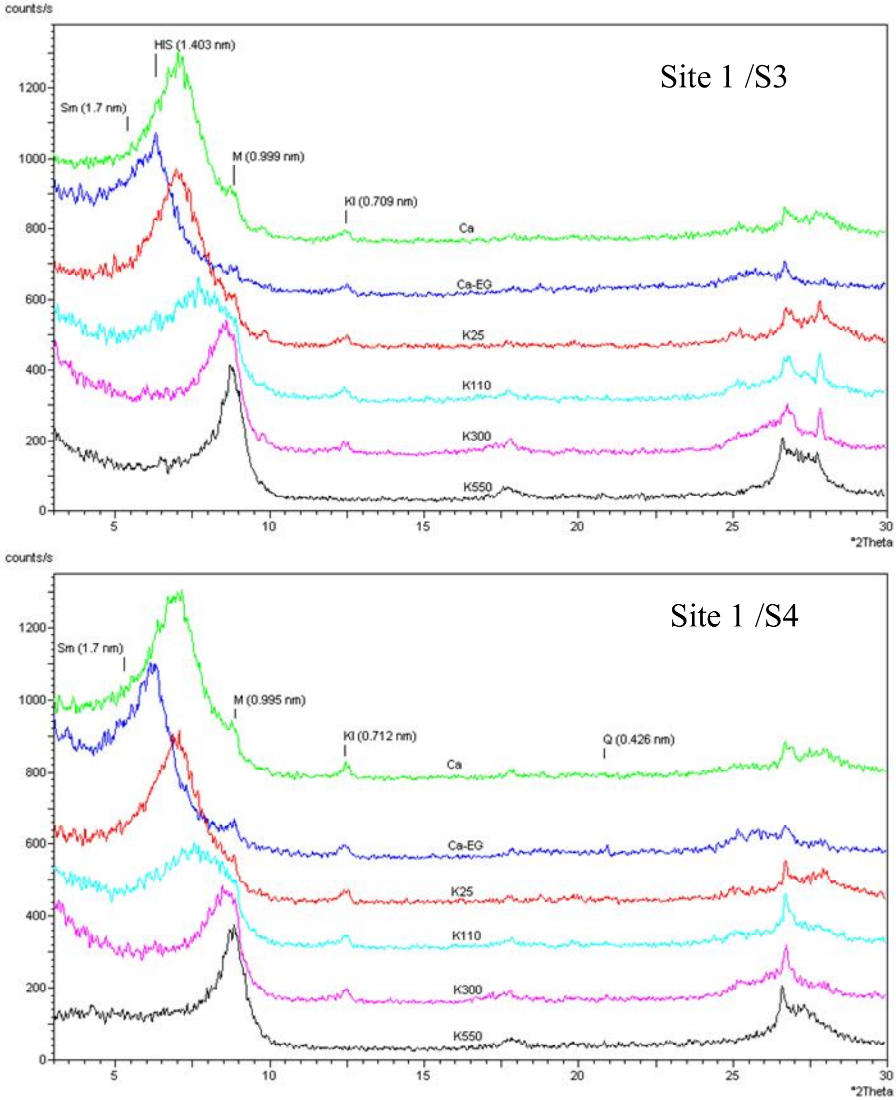

counts/s
HIS (1.403 nm)
Sm (1.7 nm)
M (0.999 nm)
Kl (0.709 nm)
Site 1 /S3
Ca
Ca-EG
K25
K110
K300
K550
°2Theta
counts/s
Sm (1.7 nm)
M (0.995 nm)
Kl (0.712 nm)
Q (0.426 nm)
Site 1 /S4
Ca
Ca-EG
K25
K110
K300
K550
°2Theta

Fig 6b

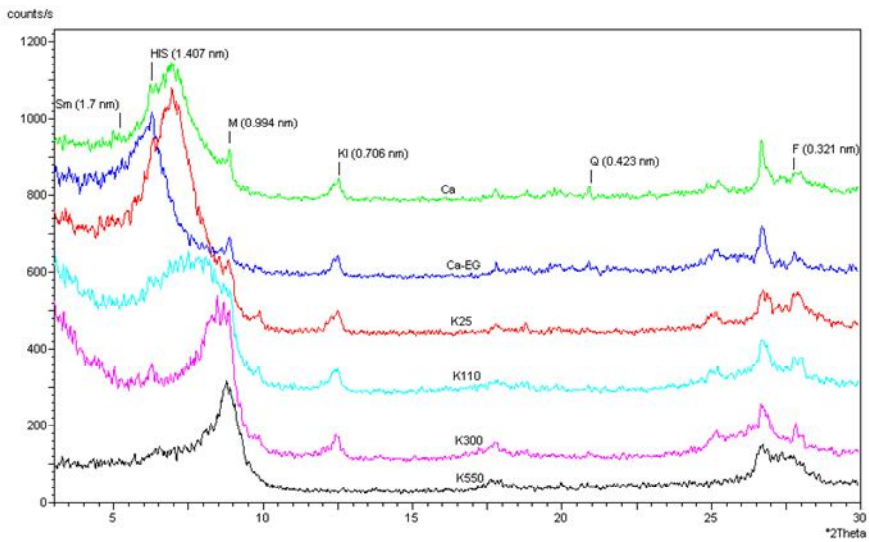


Fig 6c

Fig. 6a-6c. These diagrams reveal the X-ray diffractograms of five samples taken from different depths within a lithosection. The first curve shows Ca saturated sample, the main peak is at 70 2 theta with 1.4 nm intensity. With glycolation, it migrates to the left and then to the right with progressive heating after K saturation. There is no depth wise variation in the pattern.

The general pattern of the XRD for all the samples are near identical to each other. For the first site (Fig. 6a to 6c) the patterns are the followings:

The uppermost graph describes the first run at room temperature with Ca saturation. The main peak is identified at 7^0 2 ϴ with 1.4 nm. Another peak is identified at 9^0 2 ϴ with 0.993 nm intensity. The sample after ethanol glycolation at 60°C shows the shift in its main peak to 1.7 nm as shown by the second graph in the diagram. This indicates HIS (hydroxy interlayer smectite). The following four graphs in the diagram demonstrate the X-ray patterns of the sample after potassium saturation and heated at different temperatures such as at 25^0C, 110^0C, 300^0C, and finally at 550°C. The main peak slowly migrates to the right with progressive heating and stands at 9^0 2 ϴ with 0.987 nm. It is also observed that with the increase of the depth, feldspar, quartz and kaolinite disappear successively. A small amount of mica can be traced in some of the samples. There is smectite in small amount as well. The most prominent clay is HIS (hydroxy interlayer smectite) in all the samples from this site. The identification scheme of the clay minerals is presented in Table 3.

Table 3. Scheme for the identification of clay minerals (in Å).

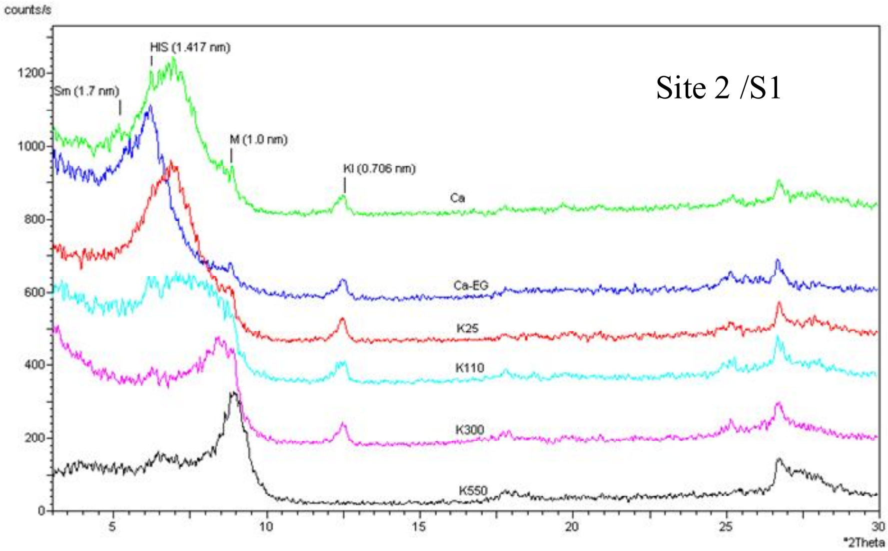
	Ca	*Ca-EG*	*K 25*	*K 110*	*K 300*	*K 550*
Mica	10	10	10	10	10	10
Kaolin	7	7	7	7	7	-
Vermiculite	14	14	10	10	10	10
Smectite	14	17	10-12	11-12	~10	10
Chlorite	14	14	14	14	14	14

Kl – Non-stable at 550°C heating; Sm – Swells to 17^0 Å on glycolation; Vermiculite – Converts to 10^0 Å on K saturation and heating; Chlorite – Stable at 550°C

The second site (Fig. 6d to 6f) shows almost the same trend as the previous site indicating a common source of sediments for both samples. In this sample, the main peak is also at 1.415 nm that migrates to the left and stands at 1.7 with glycolation. This is HIS. There are also mica and kaolinite in this sample. The main peaks move to the right with progressive K heating, exactly in the way seen in the clays of the samples of the site 1 (Fig. 5a and 5b). At 550°K, chlorite shows up at 6.5 2^0 with 1.359 nm. Feldspar appears at 27.5^0 2 ϴ with 0.321 nm with the depth. With progressive depth, small amounts of smectites, mica and kaolinite also appeared. XRDs do not reflect major depth wise variations regarding both sample sites.

4. Discussion

The examination of the quartz sand grains under the scanning electron microscope revealed several interesting features. Sand grains show equal percentage of mechanical and chemical features. The predominant features are conchoidal breakage pattern, flat as well as deformed cleavage planes, arc shaped semi-parallel steps, upturned plates, both mechanical and chemical v-notches, solution pits, grooves, razor-sharp hacksaw terminations and irregular precipitation surfaces. The conchoidal breakage pattern, cleavage planes and the semi parallel arcuate steps are indicative of the source material. Some quartz grains show the rounding of the edges associated with v-shaped indentations, which according to Krinsley and Doorncamp (1973) are the proof of subaqueous transportation. During the sediment transport under the subaqueous environment, sediment of various sizes collide and grind against each other causing enormous compression that finally results in the splitting and chipping of the grains.


counts/s
Site 2 /S1
Sm (1.7 nm)
HIS (1.417 nm)
M (1.0 nm)
Kl (0.706 nm)
Ca
Ca-EG
K25
K110
K300
K550
°2Theta

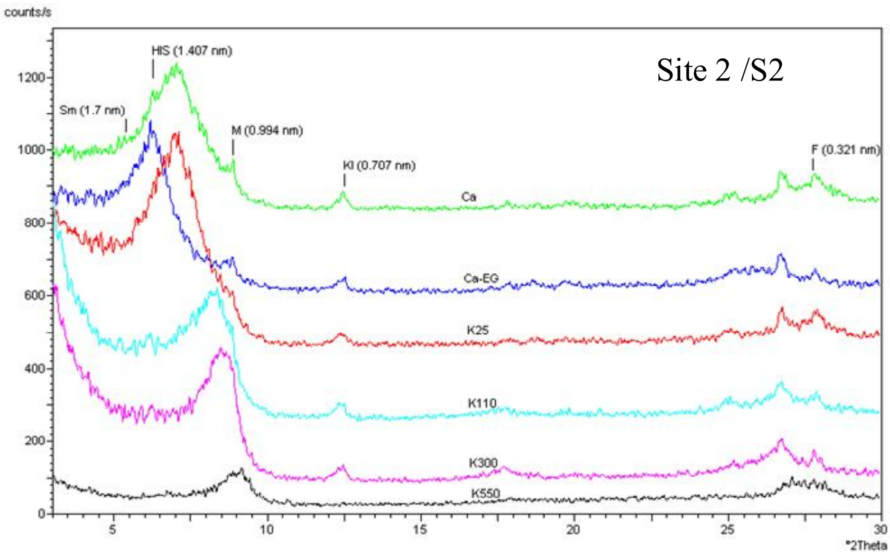
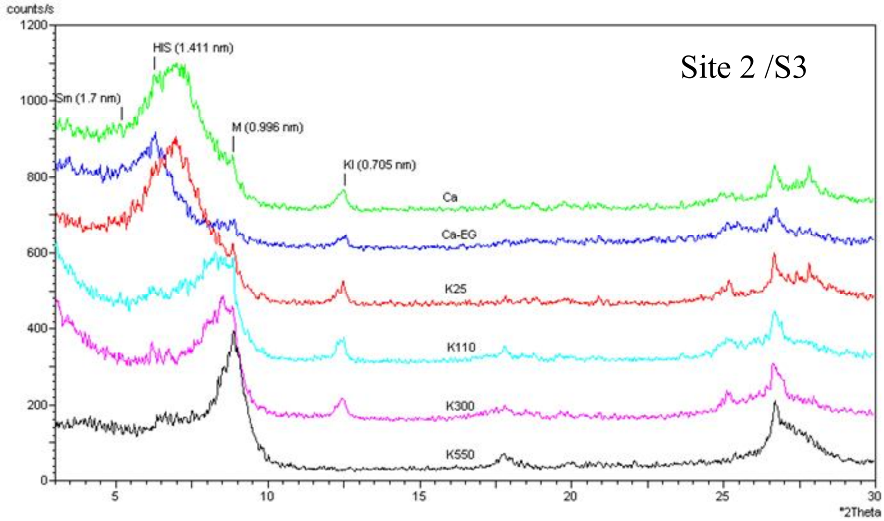

counts/s
Site 2 /S2
Sm (1.7 nm)
HIS (1.407 nm)
M (0.994 nm)
Kl (0.707 nm)
F (0.321 nm)
Ca
Ca-EG
K25
K110
K300
K550
°2Theta

Fig 6d


counts/s
1200
1000
800
600
400
200
0
HIS (1.411 nm)
Sm (1.7 nm)
M (0.996 nm)
Kl (0.705 nm)
Site 2 /S3
Ca
Ca-EG
K25
K110
K300
K550
5
10
15
20
25
30
°2Theta

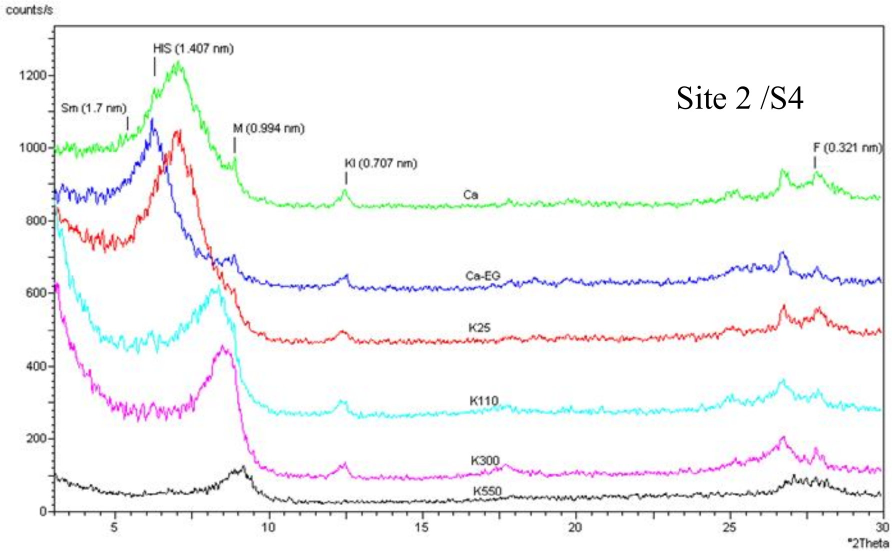

counts/s
1200
1000
800
600
400
200
0
HIS (1.407 nm)
Sm (1.7 nm)
M (0.994 nm)
Kl (0.707 nm)
F (0.321 nm)
Site 2 /S4
Ca
Ca-EG
K25
K110
K300
K550
5
10
15
20
25
30
°2Theta

Fig 6e

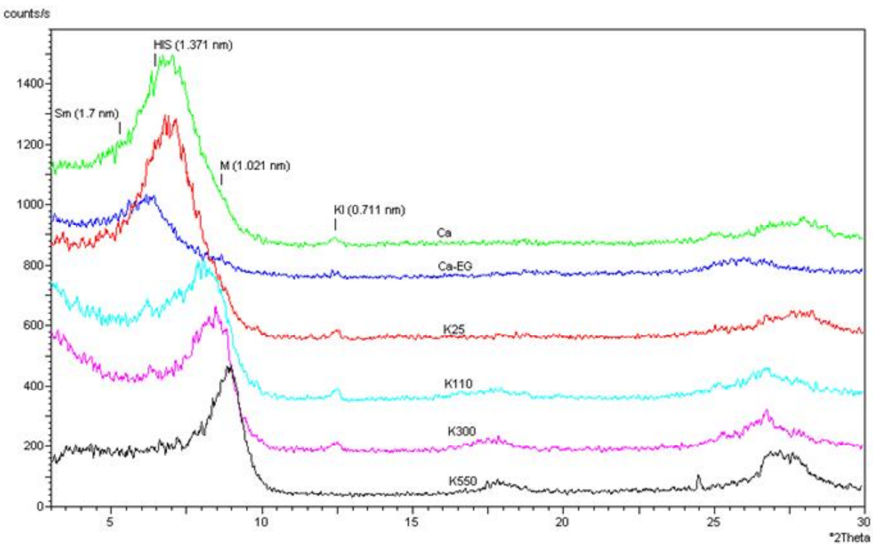


Fig 6f

Fig. 6d to 6f. These samples were also taken from different depths of the second lithosection, 18 km downstream from the first section. Similar patterns were also observed regarding these curves. Quartz cannot be seen in any of the diffractograms and feldspar appears in two samples.

Furthermore, the examination of the grain surface features also reveals that grains have undergone digenetic changes after deposition. There are features on many grains that have been considered as the result of low energy fluviatile environment such as silica precipitation and minor solutions (Tiwari et al. 2004). Some features show evidence of intense weathering such as solution crevasses and v-etching. V-patterns are produced as a result of selective chemical etching of cleavage planes. Etching along the two cleavages produces the v- shape at their intersection (Doorncamp, 1974). Whenever the v's are structurally controlled, they have a preferred direction of orientation. In the present study, the photo No. 10 in Fig. 4c is the example of this type.

Irregular solution and precipitation surfaces have been produced during the meteoric digenesis, when quartz sediments are eaten up by the carbonic cement (Kale, 1996). According to Pettijohn (1984), razor-sharp hacksaw terminations are the indicative of intrastratial solution during the diagenesis of sediments, and they are found on some grains of the samples.

The XRD of the clay fractions (<2 and <0.2 mm) indicates similar mineralogical composition showing the presence of very small amount of smectite, the dominant presence of hydroxyl-interlayered smectite (HIS), a very small amount of mica and kaolinite (smectite-kaolinite, Sm/K) and traces of vermiculite. The occasional presence of chlorite was also confirmed. There is mica in only a few of the fine clays. The presence of vermiculite was confirmed by the reinforcement of the 10^0 Å region peak on K saturation and heating.

The main peak in all the XRDs shows up at about 7° 2-theta, exactly with 1.4 nm intensity. With EG (ethylene glycolation) it migrates to the left, indicating expanding layers of smectitic nature. Then it stands fast after K-saturation, a definite sign of the presence of Al-hydroxy interlayer. It is confirmed by the laziness of right-hand migration (interlayer contraction) with progressive heating that is only completed at 550° C. This behavior can definitely interpreted as HIS; HIV (hydroxyl-interlayered vermiculite) would not shift that much with EG, and clean smectite would close its interlayers immediately after K-saturation.

The parent material is originated from the Deccan Basalt area of the Western Ghats. This mountain runs north to south for a distance of 1600 km along the western edge of the Deccan Plateau, and separates the plateau from a narrow coastal plain along the Arabian Sea. These hill ranges cover an area of 60,000 km^2 and form the catchment area of a complex river system that drains almost 40% of India. The basaltic composition of this formation is mainly phenocrysts of plagioclase, pyroxene and olivine. Quartz does not form a major component of this basalt but quartz veins are very commonly found all over the formations. The first weathering product of this Deccan Basalt (DB) is the dioctahedral smectite (Pal and Deshpande, 1989). The Deccan Basalt does not contain micaceous minerals. Thus, the presence of 1.4 nm mineral on Ca saturation and glycolation can not be vermiculite. Vermiculite is generally the alteration product of mica. The parent material impoverished with mica can not produce so much of 1.4 nm mineral. Thus it is safely presumed that 1.4 nm mineral is the hydroxyl-interlayered smectite, and a part of 1.4 nm is still smectite which expanded to 1.7 nm on glycolation.

It is possible that the samples have quite low-charge montmorillonite with significant Al. This would imply that clays have been exposed to acid soil conditions since incomplete hydroxy-interlayering is strictly a soil phenomenon. Recent soils are not acid, hence they were re-saturated or clays were washed from older soils. Overall, they do not quite look out of place in a basalt world.

5. Conclusion

Textural analysis reveals that sand-silt percent constitute for more than 70% in almost all the analyzed samples. The particle size statistics of these samples demonstrates that all the samples are very poorly sorted indicating variability in energy level of the depositing medium. Grain size probability curves demonstrate the prevalence of the three size population of surface creep, saltation and suspension. Sorting is very poor regarding all the samples that belong to all the three populations.

The grain surface features of quartz grains show equal percentage regarding mechanical and chemical features. Several features that are the result of the subaqueous transportation such as choncoidal breakage, arc-shaped semi parallel steps, v-shaped indentations, flat and deformed cleavage surfaces and grooves are observed on the grains. Grains were subjected to grinding and colliding against each other during the subaqueous transport, hence caused splitting and breaking, producing these features. Few grains reveal features of intense chemical alteration such as oriented v-pits and razor-sharp hacksaw terminations etc. An overall assessment of the features suggests that the grains are not of a very ancient origin.

The XRD of the clay fractions (< 2 and < 0.2 mm) shows the presence of very small amount of smectite, the dominant presence of hydroxy-interlayered smectite (HIS), a very small amount of mica and kaolin (smectite-kaolinite, Sm/K), and traces of vermiculite. The reinforcement of the 10^0 Å region peak on K saturation and heating confirms the presence of vermiculite but only in low quantity. There is the occasional presence of chlorite. However, a few of the fine clays do not contain mica.

Nowadays, the studied area is experiencing semi arid climatic condition. Under such a condition, the transformation of smectite to HIS and smectite to kaolinite is not possible. So this transformation occurred in a condition far more humid than the present one. Either the region has undergone a major shift in the climate or the source region of the sediments is elsewhere. Two probable explanations can be offered here. The first possibility is that owing to the massive thickness of sediment and the ephemeral nature of rivers flowing through the semi-arid study area today, it is presumed that the rivers were considerable in the geological past. With the formation of the Western Ghats during the Plio-Pleistocene crustal movement, the humid climate of the Miocene-Pliocene got replaced by semi-arid conditions which continue to prevail up to nowin the area. The Arabian Sea currently confronts the Western Ghats which rise precipitously across to an average height of 1200 m. The result is a heavy orographic rainfall all along the west coast. The lee-side towards the east including our study area receives less than 800 mm rainfall and is typically rain-shadowed (Rajaguru and Korisettar, 1987). The second explanation can be that the sediments were originated from the more humid areas of Western Ghats, transported downstream and deposited on the present locations. Based on the interpretations of the mineralogical data both explanations could be valid, but if we consider the results of scanning electron microscopic studies of the quartz grains, the second possibility is more prevalent since the features documented on these grains do not suggest the grains of such ancient origin. Although the exact age of the sediments is not known, most of the grains appear fresh. Many grains show rounding of the edges associated with v-shaped indentations that are diagnostic of subaqueous transportation. Digenetic features such as solution and silica precipitation are found on several grains that have been considered as the result of low energy fluviatile environment. An overall assemblage of the results point to the possibility that the samples belong to a population transported and deposited by fluvial agents of recent origin. How recent is this is not known at the moment. Fig. 7 demonstrates the diagrammatic representation of the transformation of smectites under the humid tropical environment (after Joshi and Tambe, 2009).

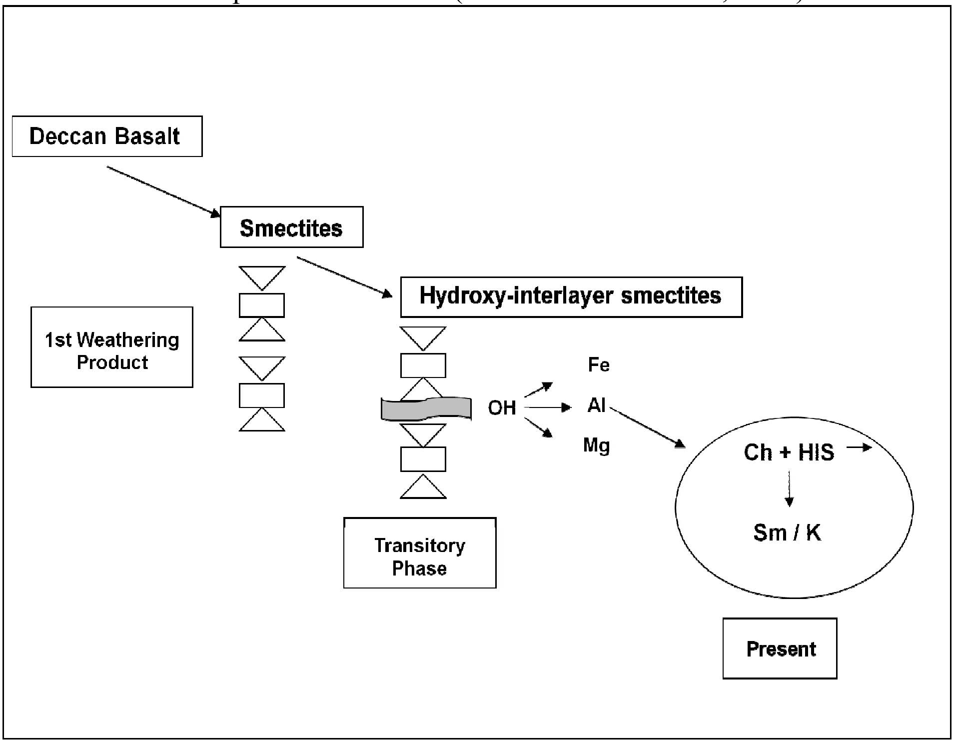


Fig. 7. Weathering of Deccan Basalt and further transformation of the 2:1 clay smectites to HIS and kaolin. During the transitory phase the interlayer between the 2:1 clay minerals have been filled with Al-, Fe- and Mg-oxides and the present condition is the transformation into HIS with small amounts of clean smectites and kaolinite (Joshi and Tambe, 2009)

Thus, it is quite likely that both HIS and Sm/K are generated in the tropical humid climate of the Western Ghats and then carried through the exiting river system like

Godavari, Pravara, Adula and Mahalungi and perhaps far downstream. The combined results of mineralogical investigation and SEM studies suggest that the sediments stored at many locations nowadays along the river banks of Western Deccan Trap region are the product of a climate far more humid than the one prevailing at these localities today.

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